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Decadal analysis of impact of future climate on wheat production in dry Mediterranean environment: A case of Jordan

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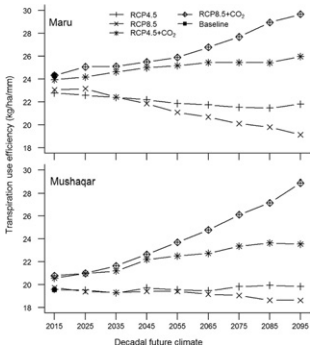
HIGHLIGHTS

- Decadal impact of climate change on wheat yield was assessed in Jordan.
- Future wheat yield due to climate change will increase in Jordan and in similar dry Mediterranean environment.
- Elevated CO_2 levels negate the adverse impact of climate change on wheat yield.
- Reduced crop cycle offers opportunity to deploy longer duration varieties that may yield more.

GRAPHICAL ABSTRACT



Transpiration use efficiency (kg ha^{-1} mm^{-1}) of wheat yield production for baseline and decadal future climate based on RCP4.5 and RCP8.5 climate change scenarios, with and without considering CO_2 response, at Maru and Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

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ABSTRACT

Different aspects of climate change, such as increased temperature, changed rainfall and higher atmospheric CO_2 concentration, all have different effects on crop yields. Process-based crop models are the most widely used tools for estimating future crop yield responses to climate change. We applied APSIM crop simulation model in a dry Mediterranean climate with Jordan as sentinel site to assess impact of climate change on wheat production at decadal level considering two climate change scenarios of representative concentration pathways (RCP) *viz.*, RCP4.5 and RCP8.5. Impact of climatic variables alone was negative on grain yield but this adverse effect was negated when elevated atmospheric CO_2 concentrations were also considered in the simulations. Crop cycle of wheat was reduced by a fortnight for RCP4.5 scenario and by a month for RCP8.5 scenario at the approach of end of the century. On an average, a grain yield increase of 5 to 11% in near future *i.e.*, 2010s–2030s decades, 12 to 16% in mid future *i.e.*, 2040s–2060s decades and 9 to 16% in end of century period can be expected for moderate climate change scenario (RCP4.5) and 6 to 15% in near future, 13 to 19% in mid future and 7 to 20% increase in end of century period for a drastic climate change scenario (RCP8.5) based on different soils. Positive impact of elevated CO_2 is more pronounced in soils with lower water holding capacity with moderate increase in temperatures. Elevated CO_2 had greater positive effect on transpiration use efficiency (TUE) than negative effect of elevated mean temperatures. The change in TUE was in near perfect direct relationship with elevated CO_2 levels ($R^2 > 0.99$) and every 100-ppm atmospheric CO_2 increase resulted in TUE increase by 2 kg ha^{-1} mm^{-1}. Thereby, in this environment yield gains are expected in future and farmers can benefit from growing wheat.

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1. Introduction

The phenomenon of climate change has a great impact on the global and regional crop production. The trends of climate have been fairly rapid in many agricultural regions around the world especially, over the past few decades along with the increases in atmospheric carbon dioxide (CO_2) concentration levels. Its impact on food security (FAO et al., 2013) is virtually certain as the aggregate productivity of global agriculture will be affected (Lobell and Gourdji, 2012). Changes in air temperature, seasonal rainfall patterns and atmospheric CO_2 concentration are key drivers of the responses of crops to climate change and expected to affect crop production worldwide (Hatfield et al., 2011; Ludwig and Asseng, 2006). All these drivers have different effects on plant production and crop yields. In combination, these effects can either increase or decrease plant production and the net effect of climate change on crop yield depends on interactions among these factors. While the impact of climate change through increased temperatures and decreased and erratic rainfalls (IPCC, 2007, 2014) is often negative, except in regions of high latitudes where temperatures are below the optimal range for wheat and impact is often positive (Mariani, 2017), the impact of elevated CO_2 may increase plant production and yield due to higher rates of photosynthesis and increased transpiration use efficiency through reduced transpiration (Amthor, 2001; Kimball et al., 1995; Long et al., 2004; Singh et al., 2014b; Sommer et al., 2013). This could partially negate the detrimental effects of rising temperatures depending on the degree of the temperature rise and the extent of reduction in crop transpiration under elevated CO_2 (Singh et al., 2014a) especially, for C_3 crops like wheat (Leakey et al., 2006).

Over the next few decades, CO_2 trends will likely increase global yields by roughly 1.8% per decade. At the same time, warming trends are likely to reduce global yields by roughly 1.5% per decade without effective adaptation, with a plausible range from roughly 0% to 4% (Lobell and Gourdji, 2012). Global wheat production is estimated to fall by 6% for each °C of further mean temperature increase (Asseng et al., 2015). While the effects of climate change will vary greatly depending on region, at a global level however, Lobell et al. (2011) estimated that rising temperatures since 1980 have already lowered wheat yields by 5.5% without considering the effect of increasing CO_2 levels and by 2.5% considering CO_2 fertilization. As the impacts of climate change on crop production are going to vary from region to region (McGrath and Lobell, 2013), there is a need to conduct an analysis to assess the climate change impact on the region and crop of our interest.

Crop modeling studies driven by long-term daily weather data can predict the impact of climate-induced risk on crop productivity (Dixit and Telleria, 2015; Webber et al., 2014). Indeed, the most widely used tools available for estimating future crop yield responses to climate change are process-based crop models, and these are already applied extensively in different parts of the world (Challinor et al., 2014; Grossman-Clarke et al., 2001; Ortiz et al., 2008; Pirttioja et al., 2015; Rosenzweig et al., 2012, 2014; White et al., 2011). Crop simulation models have been applied to provide answers to practical production questions. For example, Ludwig and Asseng (2006) found that interactions between CO_2, temperature, and rainfall were not linear and their effects on wheat yields varied with soil type and geographical locations (Cammarano et al., 2012). Numerous crop modeling studies have been conducted over the last few decades to observe the impact of climate change on crop yield of wheat and other crops (Anwar et al., 2015; Araya et al., 2015; Cammarano et al., 2012; Luo et al., 2005, 2009, O'leary et al., 2015; Singh et al., 2014a, 2014b; and Yang et al., 2014). Some studies consider the combined impact of future climate and atmospheric CO_2 while some ignore the CO_2 fertilization effect altogether (Lobell et al., 2008). Most of the studies assess the impact of climate change either for a certain time slice *e.g.*, 2050 or 2080 or current-near future (2010–2039), mid future (2040–2069) and the end of century (2070–2100) and do not expand the studies to decadal level *i.e.*, assessing climate change impact along with CO_2 for each decade until the end of century based on climatic variables and CO_2 concentration for each decade. Often the information lacks on the nature and magnitude of the impact of potential climate change scenarios at the local level and on the best strategies and crop management which can be practiced to effectively adapt to climate change (Cammarano et al., 2012). The region of our interest is the dry Mediterranean climate in countries of the Middle East and North Africa (MENA) with sentinel sites in Jordan. Only one study (Al-Bakri et al., 2011) conducted climate change impact on rain-fed agriculture in Jordan but they did not consider effect of CO_2. Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) of Intergovernmental Panel on Climate Change (IPCC) projects higher global warming and reductions in growing season rainfall especially, in Mediterranean type environments (Luo et al., 2005). Rainfed agriculture is likely to be the most sensitive sector to climate change in Jordan where wheat is the main rainfed field crop in areas that receive >350 mm rainfall for both local farmers and Bedouins (Al-Bakri et al., 2011) along with neighboring northern Syria which lie in the eastern Mediterranean region of MENA that is a prime example of the subtropical dry areas of the world (Ryan et al., 2006). In fact, across MENA, wheat (*Triticum aestivum* L. and *Triticum turgidum* ssp. *durum*) is the main staple food and wheat-based cropping systems dominate the zone delineated by the 350–600-mm isohyets (Moeller et al., 2014). Indeed, Jordan encourages wheat production through a price subsidy to producers as there is a wide gap in wheat demand and production and there are projects to enhance food security that focus primarily on improving wheat production and yield in wheat-based agricultural systems and hence the wheat production is very important for food security in this region (Al Hiary et al., 2015). According to the trade ministry of Jordan, Jordan imports over 96% of its wheat needs as domestic production covers only around 4% of demand. (Source: http://www.albawaba.com/business/grain-jordan-import-654790. Accessed 17 November 2015). Looking at the trend of wheat production since 1961, the average wheat production between the decade of 1961–70 was 147,540 with an average productivity of 612 kg ha^{-1}. Historically, the Government of Jordan has encouraged technology adoption among farmers through several means including use of improved seed varieties, agro-techniques, water harvesting techniques, integrated pest management along with extension and support to minimum guarantee prices (Momany, 2001). Since the 1970s several national and international institutions, including the Ministry of Agriculture, the Arab Center for Studies of Arid and Dry Lands (ACSAD), and the International Center for Agricultural Research in the Dry Areas (ICARDA), introduced national breeding programs using adapted foreign wheat varieties to promote use of improved seed varieties. Due to these interventions, while the average wheat grown area has declined from 238,449 ha in 1961–70 to 20,100 ha in the 2005–2014 period, the average productivity has increased to 1068 kg ha^{-1} with a total average wheat production of 21,671 tons in 2005–2014 period. (Source: FAOSTAT online database, 2017. Available at http://www.fao.org/faostat/en/?#data/QC).

Hence it makes sense to assess the impact of future climate on wheat production particularly in Jordan, which also represents the MENA region with a dry Mediterranean climate. Soils with different water holding capacities may affect wheat yield differently (Luo et al., 2009; Yang et al., 2014) and so may the sites with different precipitation and soil water levels (Kimball et al., 1995; Long et al., 2004; Mitchell et al., 2001; Sommer et al., 2013; van Ittersum et al., 2003). The degree of reduction in transpiration due to elevated CO_2 is another variable which will impact the yield and water requirement of crops (Ludwig and Asseng, 2006; Singh et al., 2014a; Sommer et al., 2013). Looking at the above, it appears important to assess the impact of climate change on wheat production in this environment especially, including the effect of elevated CO_2 due to climate change. Most of the previous researchers have used SRES scenarios and climate data from general circulation models (GCMs) utilized in the Fourth Assessment Report (AR4) of (IPCC, 2007). However, these have been recently superseded by the representative concentration pathways (RCPs) scenarios (IPCC, 2014;

Meinshausen et al., 2011; van Vuuren et al., 2011) and climate data from GCMs used in Coupled Model Intercomparison Project Phase 5 (CMIP5) described by Taylor et al. (2012) (more details in Materials and methods section). This warrants an updated climate change impact study on wheat production in this region. In this view, the objectives of this study are to i) assess the decadal impact of climate change in dry Mediterranean environment with two sentinel sites in Jordan ii) analyze the impact difference in soils with high and low water holding capacity and iii) if the future climate is favorable due to CO_2 effect, evaluate the extent of yield benefits and improvement in transpiration use efficiency in this environment.

2. Materials and methods

2.1. Study sites

Two sites in Jordan were selected *viz.*, Maru (32.55°N, 35.85°E, Altitude 620 m) and Mushaqar (31.77°N, 35.77°E, Altitude 790 m). Wheat is grown in these sites and the Field Crops Research Department of the National Center for Agricultural Research and Extension (NCARE), Jordan has maintained its research stations at these sites. Maru site is characterized as the heavy clay soil type whereas Mushaqar site is characterized as the clay loam soil type representing sites with higher and lower water holding capacity, respectively. Yang et al. (2014) reported that the crop yields are generally closely related to the water holding capacity of the soil so, selecting two representative sites with different water holding capacity of soils make a reasonable choice for the study. More than 90% of the total annual rainfall in these sites predominantly occurs from November to May, for about seven months, on which the cropping seasons lie. The mean maximum and minimum temperatures and total rainfall for each month is given in Fig. 1. Maru receives long-term mean annual rainfall of 460 mm and seasonal rainfall of 431 mm whereas Mushaqar receives long-term mean annual rainfall of 400 mm and seasonal rainfall of 379 mm (Table 1). These rainfall values are representative of the baseline climate.

2.2. Climate data and climate change scenarios

Baseline and future decadal, starting from 2015 (representing 2010–2020 decade) to 2095 (representing 2090–2100 *i.e.*, the last decade of this century), daily climate data were generated using the MarkSim stochastic weather generator (Jones et al., 2002). MarkSim is capable of generating climate data at daily time step, that is bias corrected and can be used in crop models (Dixit et al., 2011). It divides the world into 720 clusters of climate that are distinct from one another and fits a third order Markov model to the precipitation data. Subsequently, it generates the climate through interpolation of climate surfaces incorporated in the model. Details about generation of daily values of rainfall, maximum and minimum temperatures and solar radiations by MarkSim can be found in Jones et al. (2002) and Jones and Thornton (2013).

Jones and Thornton (2013) have developed MarkSimGCM web application that uses the MarkSim application at 30 arc-second climate surface (or 1-km spatial resolution) derived from WorldClim (Hijmans

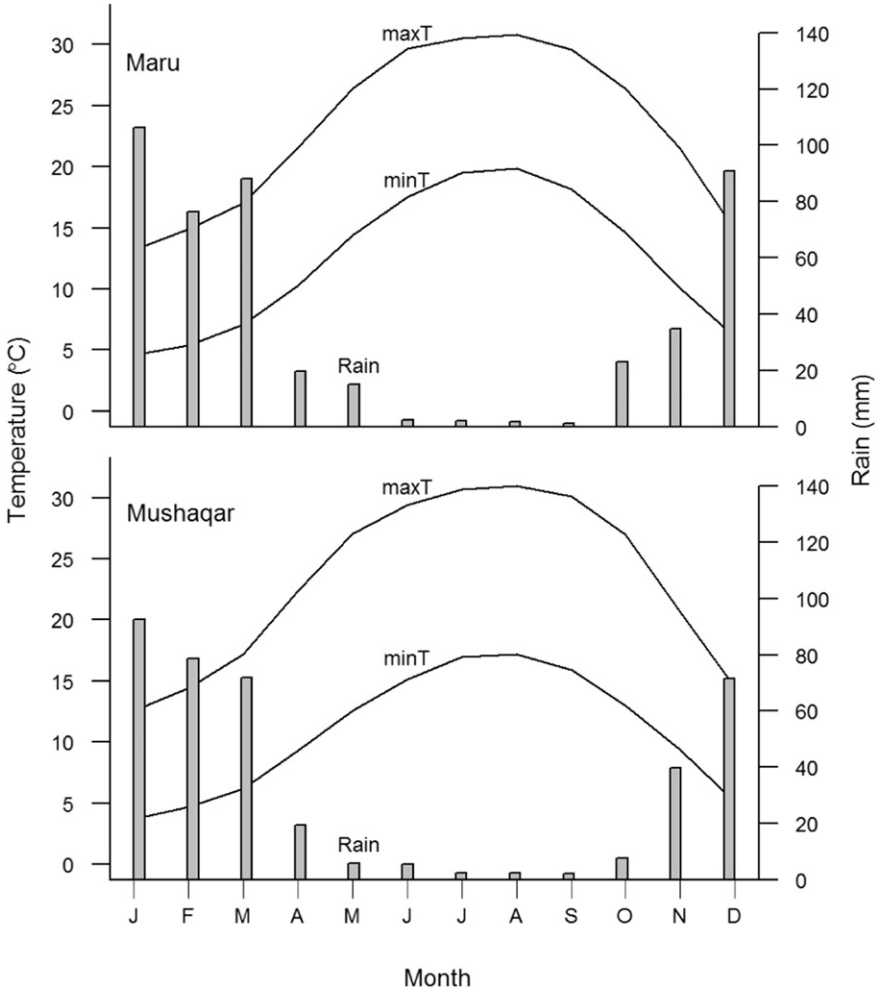

Fig. 1. Baseline climate, monthly maximum (maxT) and minimum (minT) temperatures (°C) and rainfall (mm), at Maru and Mushaqar, Jordan.

Table 1
Mean annual and seasonal rainfall, mean annual maximum and minimum temperatures and atmospheric CO_2 concentration for baseline climate and climate at decadal future period based on RCP4.5 and RCP8.5 climate change scenarios at Maru and Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

	Mean annual rainfall (mm)		Mean seasonal rainfall (mm)		Mean annual maximum temperature (°C)		Mean annual minimum temperature (°C)		Atmospheric CO_2 concentration (ppm)	
Year	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Maru										
Baseline	461.3		430.9		23.1		12.3		350.0	
2015	450.5	439.2	420.7	412.9	24.0	24.1	13.3	13.3	400.0	401.6
2025	429.1	426.5	400.8	399.5	24.4	24.6	13.6	13.8	422.7	431.5
2035	430.7	414.3	400.0	389.3	24.8	25.1	13.9	14.2	447.8	467.9
2045	433.1	406.5	404.1	380.9	25.1	25.6	14.2	14.7	473.8	513.5
2055	421.5	399.1	393.2	378.1	25.4	26.2	14.5	15.3	498.5	570.5
2065	408.0	391.5	386.2	370.5	25.7	26.8	14.7	15.9	517.6	639.3
2075	397.2	387.3	376.0	368.2	25.9	27.5	14.9	16.5	529.0	717.0
2085	407.1	380.9	387.5	364.1	26.1	28.2	15.1	17.1	532.2	801.0
2095	404.9	366.0	384.1	348.6	26.1	28.8	15.1	17.8	536.0	890.0
Mushaqar										
Baseline	399.7		379.1		23.1		10.8		350.0	
2015	402.9	396.6	382.0	376.2	24.1	24.2	11.8	11.8	400.0	401.6
2025	401.4	392.4	379.4	371.6	24.5	24.6	12.1	12.3	422.7	431.5
2035	388.9	380.4	368.3	357.4	24.8	25.1	12.5	12.7	447.8	467.9
2045	386.0	387.0	366.1	366.1	25.2	25.7	12.8	13.3	473.8	513.5
2055	390.1	369.1	372.4	348.6	25.5	26.3	13.1	13.9	498.5	570.5
2065	387.9	393.9	369.8	374.8	25.7	26.9	13.3	14.5	517.6	639.3
2075	375.3	390.4	358.6	369.2	26.0	27.5	13.5	15.1	529.0	717.0
2085	394.9	391.5	375.1	367.9	26.1	28.2	13.6	15.8	532.2	801.0
2095	404.6	387.2	383.9	359.5	26.2	28.8	13.8	16.4	536.0	890.0

et al., 2005). The new version of MarkSimGCM was developed for the GCMs used in Coupled Model Intercomparison Project Phase 5 (CMIP5) described by Taylor et al. (2012). It uses 17 GCMs from the CMIP5 that were considered in the IPCC Fifth Assessment Report (AR5) (IPCC, 2014). Recently, IPCC AR5 has developed climate change scenarios, based on the CO_2 concentration in the atmosphere using CMIP5 data covering spectrum of plausible radiative forcing scenarios, that are called representative concentration pathways (RCPs).

The RCPs are characterized by the radiative forcing *i.e.*, the extra heat the lower atmosphere will retain as a result of additional atmospheric concentrations of carbon dioxide and other greenhouse gases, measured in W m^{-2}, produced by the end of the 21st century (van Vuuren et al., 2011). The complex nature of humanity's possible future emissions has been reduced to just four representative pathways. These are termed as RCP8.5, RCP6.0, RCP4.5 and RCP2.6 and are based on a range of projections of future population growth, technological development, and societal responses. RCP8.5 (Moss et al., 2010; Riahi et al., 2011) is similar to the highest-emission scenario (A1FI) in the IPCC Fourth Assessment Report (AR4) and arises from little effort to reduce emissions and represents a failure to curb warming by 2100. The greenhouse gas emissions and concentrations in this scenario increase considerably throughout the 21st century before reaching a level of about 8.5 W m^{-2} at the end of the century. In addition to this high scenario, there are two intermediate scenarios, RCP4.5 and RCP6.0, and a low scenario, RCP2.6, in which radiative forcing reaches a maximum near the middle of the 21st century before decreasing to an eventual nominal level of 2.6 W m^{-2}. RCP4.5 is a scenario that stabilizes radiative forcing at 4.5 W m^{-2} in the year 2100 without ever exceeding that value while RCP6.0 is a scenario that stabilizes radiative forcing at 6.0 W m^{-2} in the year 2100 without overshooting that value (Meinshausen et al., 2011; Thomson et al., 2011). RCP4.5 is similar to the lowest-emission scenario (B1) assessed in the IPCC AR4. Emissions in RCP4.5 peak around 2040, and then decline. In RCP6, emissions peak around 2080, and then decline (Meinshausen et al., 2011).

Previous researchers (*e.g.*, Angulo et al., 2013; Anwar et al., 2015; Luo et al., 2005, 2009; Robertson et al., 2013; Singh et al., 2014a, 2014b; Sommer et al., 2013; Yang et al., 2014) have used SRES scenarios and the downscaled data from CMIP3 (Meehl et al., 2007) for mostly B1, A1B, and A2 scenarios. However, recent trend is moving towards using RCP scenarios (Araya et al., 2015; Muller and Robertson, 2014; Rosenzweig et al., 2014). Two climate change scenarios *viz.*, RCP4.5 and RCP8.5 were selected for this study. Generated baseline climate data is a representation of climate of 1961–1990. Previous studies have used benchmark of 1961–1990 as baseline climate for assessing climate change impact on wheat production using SRES scenarios (Parry et al., 2004; Singh et al., 2014a, 2014b; Sommer et al., 2013; Yang et al., 2014). For baseline and decadal climate (*i.e.,* climate for each decade), 99 years of realization of weather pattern were generated so that they can reflect the stochastic nature of weather for a particular period and provide the range of yield during long-term simulation for a particular climate change scenario. The weather variables generated were maximum and minimum temperatures (°C), rainfall (mm) and solar radiation (MJ m^{-2}) at daily time step.

Four GCMs out of 17, as incorporated in MarkSimGCM web application suite, were used to generate the climate data and finally the average of these four GCMs was used to prepare the weather data files. These four GCMs were CSIRO-Mk3.6.0 (Commonwealth Scientific and Industrial Research Organization - Mark) with 1.875° × 1.875° resolution data (Collier et al., 2011; Rotstayn et al., 2012), HadGEM2-ES (Hadley Centre Global Environmental Model version 2 Earth System configuration) with 1.2414° × 1.875° resolution data (Collins et al., 2011; Jones et al., 2011), MIROC5 (Model for Interdisciplinary Research on Climate, produced by the University of Tokyo's Center for Climate System Research) with 1.4063° × 1.4063° resolution data (Watanabe et al., 2010) and MRI-CGCM3 (Meteorological Research Institute coupled GCM version 3) with 1.125° × 1.125° resolution data (Yukimoto et al., 2012). These GCMs had higher resolution data than others in the suite of 17 GCMs incorporated in the MarkSim.

The uncertainties between the outputs of different climate models is widely recognized (Asseng et al., 2013) along with the evidence that indicates that the current generation of climate models (when run as a group, with the CMIP5 prescribed forcings) do not reproduce the observed global warming over the past 20 years, or the slowdown in global warming over the past fifteen years. Possible explanation for the discrepancy is that forced and internal variation might combine differently in observations than in models (Fyfe et al., 2013). To obtain a more comprehensive picture of impact of climate change on crop yield and the effectiveness of adaptation strategies, outputs from multiple climate

models should be applied in future climate change risk assessment (Asseng et al., 2013; Luo et al., 2009; Meehl et al., 2007). Hence in this study, we consider the outputs from four GCMs. The atmospheric CO_2 concentration levels for RCP4.5 and RCP8.5 scenarios were also considered in this study and were determined from the study of Meinshausen et al. (2011) (Meinshausen, M., personal communication, November 29, 2014, data available at http://www.pik-potsdam.de/~mmalte/rcps/). The baseline CO_2 concentration was considered 350 ppm as incorporated in the crop simulation model used for this study. The mean climate at both sites and the CO_2 concentration levels for the decadal future climate, for RCP4.5 and RCP8.5 climate change scenarios, are given in Table 1.

2.3. Long-term simulation of wheat

Long-term simulations of wheat (*Triticum turgidum* ssp. *durum*) crop cycle *i.e.,* days to maturity and yield were carried out using the Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003; McCown et al., 1996). APSIM is a crop simulation model that simulates the crop phenological development, biomass accumulation, grain yield, nitrogen and soil water balance in a farming system (McCown et al., 1996) and operates on daily time steps. The APSIM 7.5 version was used for this study. APSIM has been used across the world by various researchers for simulation of crop growth, yield and N fertilizer treatment (Akponikpe et al., 2010; Dixit et al., 2011; Dixit and Telleria, 2015; Moeller et al., 2014; Mohanty et al., 2012; Probert et al., 1998), impact assessment of climate change (Anwar et al., 2015; Araya et al., 2015; Luo et al., 2005, 2009; Ludwig et al., 2009; Yang et al., 2014), optimizing management practices *e.g.,* optimizing planting time and sowing density (Bassu et al., 2009; Zhang et al., 2012), simulation of crop physiological traits of wheat and improved wheat cultivars (Asseng et al., 2002; Luo et al., 2009) and response of wheat crop to elevated atmospheric CO_2 (Ludwig and Asseng, 2006; Asseng et al., 2004; O'Leary et al., 2015; Reyenga et al., 1999; Yang et al., 2014).

The APSIM incorporates the physiological effects of elevated atmospheric CO_2 by means of a CO_2 factor obtained from the experiment. The CO_2 concentration affects radiation-limited biomass accumulation through a CO_2 factor affecting the radiation use efficiency, transpiration efficiency through another CO_2 factor and so is the critical N concentration of the leaves. All these modifications to APSIM wheat module have been made based on CO_2 factors obtained from the observed values of plants grown under elevated CO_2 in the experiment (Reyenga et al., 1999) and not through the mechanistic modeling of *e.g.*, reduction in stomatal conductance and surface leaf area or increase in root biomass.

Asseng et al. (2002) argue, based on their simulation studies, that APSIM wheat model is able to simulate the crop-soil water and atmosphere interactions dynamics over large range of yields and environment including the Mediterranean environment similar to our study sites. They also related their results to several previous studies and affirmed the reliable performance of APSIM in wheat yield simulations over wide range of yields. APSIM has been previously applied for the simulation of wheat yield at Maru, Jordan by Heng et al. (2007) and in similar environment in Syria. The testing of APSIM performance for the conditions at Tel Hadya in Northern Syria has been described in detail by Moeller et al. (2007) and Moeller et al. (2014) and it has been further successfully applied to long-term barley simulations (Dixit and Telleria, 2015) which showed that APSIM is suitable for simulating cereal based cropping systems in this environment.

2.4. Simulation scenarios

Long-term simulations of wheat crop cycle and yield were carried out for 99 years with the generated weather data for each climate scenario *i.e.*, with baseline climate and with different scenarios of climate change as explained in Section 2.2. The crop sowing was timed to match the usual practice of sowing at the onset of rain in the sowing window of 1st November - 20th December. The sowing criterion was such that the sowing took place once the cumulative rainfall of 20 mm occurs over a period of 5 days. However, if this condition was not met, the crop was sown on the last day of the sowing window. The crop was sown at a depth of 3 cm with a plant density of 250 plants m^{-2} keeping a row spacing of 33 cm. The soil water holding capacity of heavy clay type soil at Maru and clay loam type soil at Mushaqar were 194 mm and 117 mm for a depth of 1.5 m, respectively. The simulations were initialized by setting the soil water to 50% of the water holding capacity *i.e.,* 97 mm of soil water filled from top for Maru and 59 mm for Mushaqar. This is because some moisture is already present in deeper layers at the time of sowing along with the rainfall to meet sowing criteria plus some more rainfall which has fallen before but has not met sowing criteria. The total initial mineral N was 27 kg ha^{-1} of $NO3^-$ and 12 kg ha^{-1} of $NH4^+$ while a total of 3.4% organic C was available at Maru. At Mushaqar, the total initial mineral N was 16 kg ha^{-1} of NO_3^-, 8 kg ha^{-1} of NH_4^+ and 2.4% organic C. The soil water, nitrogen and surface organic matter was reset at sowing for each year of simulation so that there was no carry over effect of depleted resources. To follow the general farmers' practice in the area, simulations were carried out with 50 kgN ha^{-1} applied at sowing. No fertilizer was applied after the crop was sown.

2.5. APSIM calibration: calibrating parameters

A local wheat cultivar 'ACSAD65', grown in the study area, was used for simulation and APSIM was calibrated to simulate crop cycle, biomass and grain yield for this cultivar following the similar procedure applied earlier to calibrate barley cultivar for this environment by Dixit and Telleria (2015). On an average, the calibration was aimed to simulate the days to flowering, days to maturity, above-ground biomass and grain yield to 92 days, 129 days, 5300 kg ha^{-1} and 2050 kg ha^{-1} respectively, as observed in Maru over several years. The choice of the crop model calibration depends on the objective of the study (Cammarano et al., 2012) and hence for this study, which looks into the impact of climate change on wheat yield and crop cycle, it was imperative to calibrate model to simulate the yield and days to maturity, which match the observed data. Hence the focus of calibration was crop cycle, biomass and yield. Despite the differences among models in their assumed inputs and simulations of absolute yields, relative yield changes provide a more consistent set of results for comparison (Rosenzweig et al., 2014). Hence, if relative change in crop cycle and yield due to climate change impact, compared to baseline, has to be seen, as in this study, any error associated with the calibration itself should have little effect.

Several cultivar parameters were changed during calibration to achieve the best fit between observed and simulated crop cycle and yield for the selected cultivar. Some of the important parameters to calibrate crop cycle were the thermal time requirements for the different development stages: (i) end of juvenile phase (ii) floral initiation (iii) flowering phase (iv) start of grain filling, and (v) end of grain filling. In addition, the photoperiod sensitivity (response to day length) and vernalization (cold temperature requirement), as incorporated in the wheat crop module of APSIM, were also adapted. Important changes made to calibrate the grain yield were (i) potential grain filling rate (ii) potential grain growth rate, and (iii) maximum grain size. These are cultivar specific parameters and require adjustment to calibrate a new cultivar. All other parameters were same as the wheat 'base cultivar' included in the APSIM suite. The calibration parameters and the model outputs during calibration are given in Table S1 (supplementary data). As a principle, once calibrated for a location, the crop model is able to simulate the variation in soil and weather conditions over other locations for the same cultivar (Boote et al., 2001; Boote, K.J., personal communication, March 17, 2014; Chenu et al., 2009; Dixit and Telleria, 2015; Mavromatis et al., 2002). Hence the calibrated APSIM was applied to Mushaqar for the long-term simulation of wheat crop cycle and yield.

2.6. Statistical comparison

Student's *t*-test (Snedecor and Cochran, 1980) was performed in R statistical software and environment (R Core Team, 2013; http://www.R-project.org/) to see the significance of change in crop cycle and yield of wheat for each decade, compared to baseline, due to the impact of climate change.

3. Results and discussion

3.1. Climate projections for different climate change scenarios

3.1.1. Mean annual and seasonal rainfall

Mean annual and seasonal rainfall were computed from the 99 realizations of the weather for a given climate change (CC) scenario. The simulations for year 2015 represent the 2010s decade (2010 − 2020) and the last decade of this century *i.e.*, 2090s or 2090–2100 is represented from the simulation of year 2095. At Maru: a higher decrease in mean rainfall, both annual and seasonal, is observed for RCP8.5 scenario than RCP4.5 scenario for a given future decade (Table 1, Fig. 2). For RCP4.5 scenario, there was 2.3% reduction in mean annual rainfall for the 2010–2020 decade. For next three decades, 2020s, 2030s and 2040s (*i.e.*, years 2025, 2035 and 2045), the decrease ranged from 6.1 to 7.0%. For 2050s, the decrease was 8.5% and for the next four decades the reduction was in the range of 11.5–14%. Highest reduction was observed for the decade of 2070s. The reduction in seasonal rainfall was similar to annual rainfall except that until 2050s decade there was slightly more reduction (maximum of 0.6% for 2030s) and afterwards slightly less reduction compared to annual rainfall (maximum of 1.7% for 2080s) (Table 1). For RCP8.5 scenario, the reduction was higher as the time progressed and for 2090s decade almost 21% reduction was observed, starting from 4.8% and 7.5% decrease in 2010s and 2020s decades, respectively from baseline. This decrease is in the decrement of 2.7% between the decades. After 2020s, the reduction is in the decrement of 1.7% for the next three decades *i.e.*, a total decrease of about 13.5% for the 2050s decade. While the precipitation, an important weather limitation to the crop yield, is difficult to simulate due to the contribution of processes working on a wide range of scales (from macro to micro, from synoptic disturbances to microscale sensible and latent heat contributions to convection), the value of bias corrected precipitation simulations and the subsequent use of such data in the crop yield simulation in the Mediterranean environment has been established in a previous study (Dixit and Telleria, 2015). Moreover, these results are similar to the findings of Ragab and Prudhomme (2002) for the period of 2050s. They conducted a simulation study of the global climate change for greenhouse gas concentration emission scenarios for the 2050s time period, using the UK Hadley Center's global climate model and reported a reduction of 10–15% in winter rainfall, *i.e.*, the rainfall during crop growing season, in the east Mediterranean countries, including Jordan.

The reduction in seasonal rainfall followed similar trend but was bit lower compared to the annual rainfall (maximum of 1.9% for 2080s). It

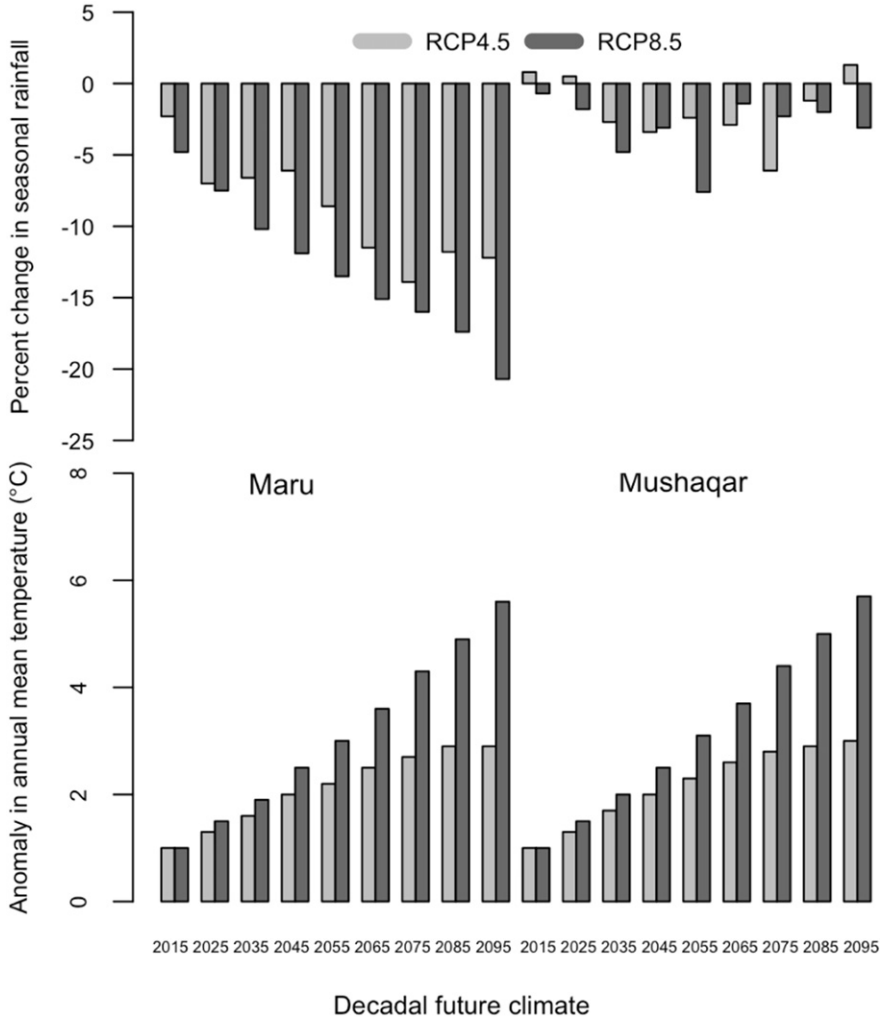

Fig. 2. Percent change in seasonal rainfall and anomaly in annual mean temperature for decadal future climate based on RCP4.5 and RCP8.5 climate change scenarios, with respect to, baseline climate at Maru and Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

shows that the impact of climate change on crop production will be little less in this environment compared to the total impact of climate change on rainfall on annual basis except for RCP4.5 scenario until 2050s decade. At Mushaqar: however, there is less drastic reduction in rainfall for RCP4.5 scenario and the maximum reduction in annual and seasonal rainfall is 6% and 5.5% for 2070s. For the first two decades *i.e.*, 2010s and 2020s there is slight (<1%) increase in the rainfall, both annual and seasonal. For RCP8.5 scenario, the maximum reduction in annual and seasonal rainfall was 7.5% and 8% respectively, for 2050s (Fig. 2). It appears that the drier of two sites (Mushaqar) has less drastic reduction in rainfall than the wetter site (Maru) for both RCP4.5 and RCP8.5 scenarios. More or less the reduction in seasonal rainfall is not much different from the reduction in annual rainfall at both the sites for both CC scenarios.

3.1.2. Mean, maximum and minimum annual temperature

There was an increase of 1 °C in annual mean temperature for year 2015 *i.e.*, the decade of 2010–2020 from the baseline for both RCP4.5 and RCP8.5 CC scenarios at both sites Maru and Mushaqar (Table 1, Fig. 2). Thereafter, until the 2060s decade, the temperature increased at an average of 0.3 °C increment for each decade from 2010s for RCP4.5 scenario at both the sites. The temperature increase for 2050s decade is about 2.2 and 3 °C at Maru and 2.3 and 3.1 °C at Mushaqar for RCP4.5 and RCP8.5 scenarios, respectively. These results agree with the rise in temperature of 1.75 to 2.75 °C predicted for 2050s time period in the east Mediterranean countries, including Jordan by Ragab and Prudhomme (2002). The results are also similar, albeit to a lesser extent, to the increase in temperature of 0.34 to 1.67 °C, simulated with three GCMs in the Northern Jordan (where Maru site is located) reported by Al-Bakri et al. (2011). An overall increase of mean annual temperatures for the entire Mediterranean region has been predicted due to climate change (Haim et al., 2008). For the 2070s, 2080s and 2090s decades the increment in annual mean temperature was 0.2, 0.2 and 0 °C at Maru and 0.2, 0.1 and 0.1 °C at Mushaqar respectively, for RCP4.5 scenario. This shows that in RCP4.5 scenario, after 2060s decade, due to the stabilization in greenhouse gas emission and concentration, the increment in mean temperature decreases until the end of the century. The maximum increase in annual mean temperature for RCP4.5 scenario was 2.9 °C, compared to baseline (Fig. 2, Table 1), in 2080s and 2090s decades at Maru and 3 °C for 2090s decade at Mushaqar. Across 18 sites in semi-arid environment of Central Asia, similar environment as in this study, an increase of 1 °C in near future (2011–2040), 2–2.5 °C in mid future (2041–2070) and 3.3–4.5 °C in long-term future (2071–2100) in mean annual temperature was reported by Sommer et al. (2013) which are quite in line with the results of our study.

In the case of RCP8.5 scenario, until 2050s decade, the average increment in annual mean temperature is 0.5 °C for each decade from 2010s and thereafter an average increment of 0.65 °C for each decade until the end of the century, at both Maru and Mushaqar. In this case the maximum increase in annual mean temperature was 5.6 °C, compared to baseline, at Maru and 5.7 °C at Mushaqar, both for 2090s decade.

The mean annual maximum and minimum baseline temperatures were 23.1 and 12.3 °C at Maru and 23.1 and 10.8 °C at Mushaqar. For RCP4.5 scenario, the increase in mean annual maximum temperature for each decade was slightly higher (0.4 °C) than the increase in annual mean temperature (0.3 °C) until 2030s for Maru and until 2040s for Mushaqar and thereafter it followed same pattern as the annual mean temperature (Table 1). For RCP8.5 scenario, the increase in mean annual maximum temperature followed same pattern as the annual mean temperature for Maru, however, slightly higher (0.6 °C) for Mushaqar for 2020s to 2060s decades compared to increase in annual mean temperature (0.5 °C). Where the increase in mean annual maximum temperature, compared to annual mean temperature, was higher, the increase in mean annual minimum temperature was proportionately lower and *vice versa*. Hence it appears that the increase in annual mean temperature is a good indicator of the magnitude of increase in mean annual maximum and minimum temperatures as well. Thus the variation in maximum or minimum annual temperature is not an issue to be taken into account during interpretation of simulation results. While the differences in rainfall between sites were evident due to climate change, no significant changes in mean, maximum and minimum temperatures were observed between the two sites for different decades and CC scenarios.

3.1.3. Atmospheric carbon dioxide concentration

The default baseline atmospheric carbon dioxide (CO_2) concentration of 350 ppm is considered in APSIM simulations. The projected CO_2 concentrations for 2010s decade are similar for both RCP4.5 and RCP8.5 scenarios *i.e.*, 400 and 402 ppm respectively. In the case of RCP4.5 scenario, the CO_2 concentration increases until 2050s with an incremental rate of 5–6%, from the 2010s decade, thereafter the increment reduces and the CO_2 concentration stabilizes in the last three decades achieving the maximum value of 536 ppm in year 2095 *i.e.*, the 2090s decade (Table 1). The CO_2 concentration was considered to be same at both the sites Maru and Mushaqar. For RCP8.5 scenario, the CO_2 concentration rises with faster rate starting from about 7.5% in 2020s decade, compared to 2010s, and reaching up to incremental increase of 12% in 2060s and 2070s decades, thereafter the increment slows to 11% in the last two decades achieving the maximum CO_2 concentration of 890 ppm in 2090s decade. However, compared to RCP4.5, the CO_2 concentration constantly increases for RCP8.5 scenario beginning from almost similar CO_2 concentration in 2010s decade (only 0.4% higher for RCP8.5) to about 66% by the 2090s decade with highest average incremental increase of about 15% in the last three decades.

3.2. Climate change impact on crop cycle

The simulated impact of climate change was conspicuous on the crop cycle, *i.e.* the number of days crop takes to physiologically mature in both the cases without considering CO_2 effect and including the effect of CO_2, in this Mediterranean dry environment at both the sites Maru (Fig. 3a) and Mushaqar (Fig. 3b). For each passing decade, the days to crop maturity consistently decline more so for the RCP8.5 scenario except for the 2010 decade. The ability of APSIM to simulate and well capture the effect of rising temperature on crop maturity of wheat in the Mediterranean environment of Australia is also reported by Sadras and Monzon (2006). Practically no impact on crop cycle was seen when CO_2 effect was included in the simulations compared to no CO_2 effect. No effect of elevated CO_2 on phenological development of wheat was observed by Ewert et al. (2002), and Pinter et al. (2000) found little evidence that CO_2 effects on stomatal conductance and leaf temperature affected phenological development of wheat in a Free-Air CO_2 Enrichment (FACE) experiment. It appears that the rising temperature effect alone explained decline in wheat maturity and CO_2 effect did not play role in it. Similar results were also reported by Mitchell et al. (1993, 1996 and 2001) where in their experiments and simulation studies, they found that the elevated CO_2 levels from 360 to 690 ppm had no effect on wheat phenology. This indicates that the increasing temperatures are mainly responsible for the crop maturity to hasten. The literature is replete with reporting of faster rate of crop growth and reduction in crop cycle due to increase in temperature (Anwar et al., 2015; Cooper et al., 2009; Ludwig and Asseng, 2006; Mitchell et al., 1993; Sadras and Monzon, 2006; van Ittersum et al., 2003). For RCP4.5 scenario, there was 6.4% and 5% decline in the days to maturity for the 2010s decade at Maru and Mushaqar respectively, and until the end of the century this trend continues culminating in 16.5% and 12% decline at Maru and Mushaqar respectively, in the last decade of the century (Table 2). Temperature increases cause the plant to develop faster and they reach maturity sooner (Ritchie and Nesmith, 1991). Higher canopy temperatures may lead to an accelerated ageing of the foliage by increasing the rate of decline of photosynthetic tissue and can shorten the crop

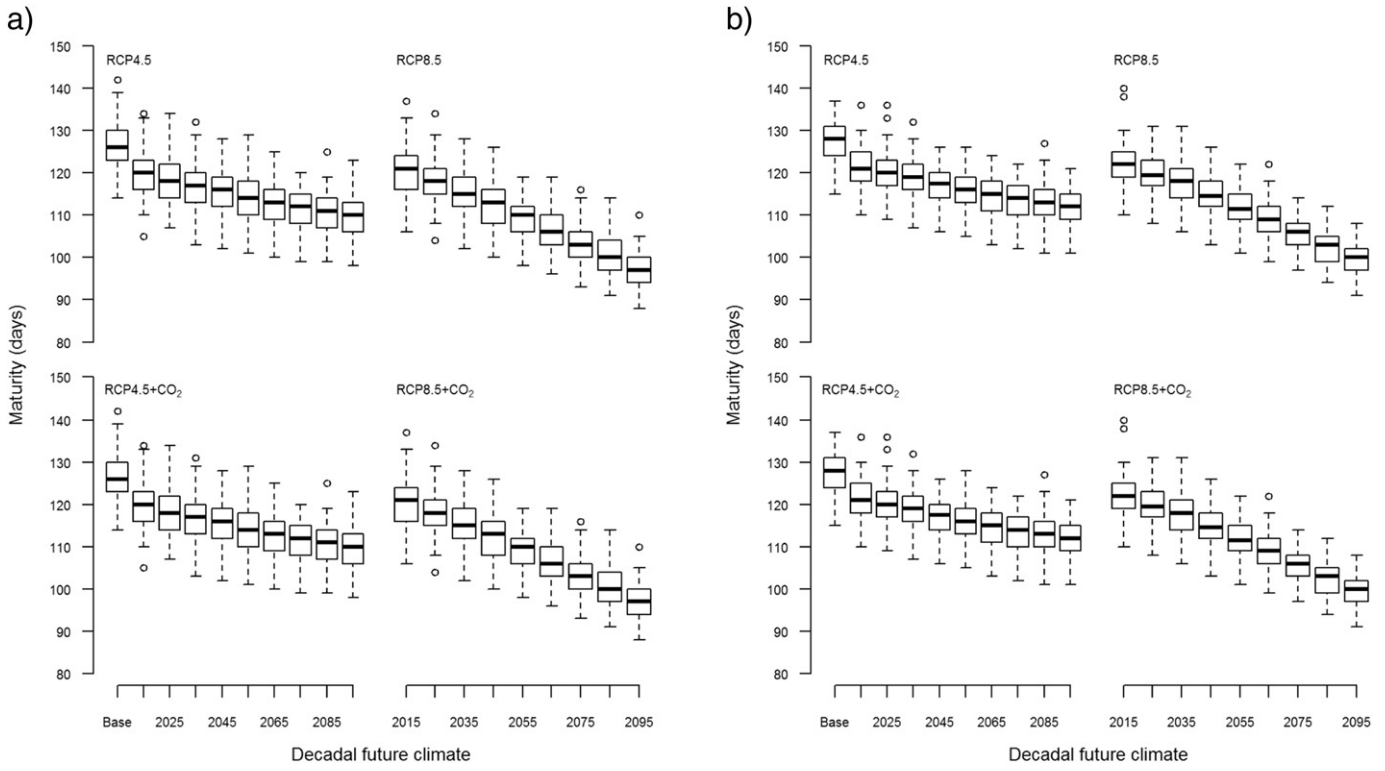

Fig. 3. Crop maturity (days) for baseline and decadal future climate based on RCP4.5 and RCP8.5 climate change scenarios, with and without considering CO_2 response, at (a) Maru and (b) Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

cycle, for example, grain-filling period which have consequences for yield (Hay and Walker, 1989; van de Geijn and Goudriaan, 1996).

An advance of 6–8 days in wheat maturity per °C temperature increase in the Mediterranean environment of Western Australia, having similar latitude as in our study, though in southern hemisphere has been reported by van Ittersum et al. (2003). Increasing air temperature by 3 °C accelerated crop development and in turn shortened the time to maturity by 13 days in wheat (Asseng et al., 2004). These results are similar to the 2080s and 2090s decades for RCP4.5 scenario and 2050s decade for RCP8.5 scenario in our study where an increase of about 3 °C cause the crop to mature about 16–17 days before at Maru and 15–16 days at Mushaqar (Figs. 2, 3a & 3b). Yang et al. (2014) found that the median maturity dates over the 12 soils type for the period of 2021–2040, for A2 scenario of SRES, which is similar to RCP8.5 scenario, hastened from 7 to 17 days across six wheat growing sites in New South Wales, having a similar climate as in our study. For 2020s, 2030s and 2040s decades, the reduction in crop maturity is 8, 11 and 14 days at Maru and 8, 10 and 13 days at Mushaqar respectively,

Table 2
Mean change in grain yield (%) and days to maturity (%) for decadal future period based on RCP4.5 and RCP8.5 climate change scenarios compared to baseline climate, with and without considering CO_2 response, at Maru and Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

	Mean change in grain yield (%)		Mean change in grain yield considering CO_2 response (%)		Mean change in days to maturity (%)		Mean change in days to maturity considering CO_2 response (%)	
Year	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Maru								
2015	−5.6	−4.3	5.1	7.6	−6.4	−5.7	−6.4	−5.7
2025	−8.0	−7.4	6.4	8.7	−8.0	−8.2	−8.1	−8.1
2035	−9.6	−7.9	9.1	14.7	−9.3	−10.9	−9.3	−10.9
2045	−10.7	−14.4	12.0	13.0	−10.6	−13.5	−10.6	−13.5
2055	−14.5	−16.2	10.8	17.7	−12.1	−17.0	−12.1	−17.0
2065	−15.0	−20.4	13.0	19.3	−13.4	−19.8	−13.4	−19.8
2075	−15.7	−26.8	13.5	16.2	−15.1	−23.2	−15.1	−23.2
2085	−17.7	−27.8	11.0	20.3	−15.8	−26.1	−15.8	−26.1
2095	−17.9	−33.0	11.5	16.4	−16.5	−29.0	−16.5	−29.1
Mushaqar								
2015	−3.6	−5.2	7.2	5.7	−5.0	−4.2	−5.0	−4.2
2025	−6.1	−6.5	8.9	9.9	−5.9	−6.1	−5.9	−6.1
2035	−8.1	−9.30	10.8	12.6	−6.9	−7.9	−6.9	−7.9
2045	−9.2	−12.1	13.8	15.8	−8.0	−10.0	−8.0	−10.0
2055	−10.8	−15.7	15.5	17.9	−8.9	−12.4	−8.8	−12.4
2065	−12.5	−21.8	15.9	16.4	−10.0	−14.7	−10.0	−14.7
2075	−13.9	−27.2	15.6	14.0	−10.9	−17.2	−10.9	−17.2
2085	−18.3	−33.3	10.0	10.1	−11.5	−19.7	−11.5	−19.7
2095	−19.5	−37.5	8.9	7.1	−12.2	−21.9	−12.2	−21.9

agreeing with the results of above study. Overall, a reduction of up to 16 and 29 days (Figs. 3a & 3b) in crop cycle for RCP4.5 and RCP8.5 scenario respectively can be expected by the end of this century at both the sites.

While overall rainfall amount is critical in determining yields, higher future temperatures due to climate change can contribute to reducing crop productivity primarily due to advanced crop phenology which renders less time for plants to intercept light for photosynthesis causing less biomass accumulation and thereby reduction in grain yield (Anwar et al., 2015; Asseng et al., 2015; Rosenzweig, 1989). Similar magnitude of reduction, as in our study, in days to maturity of wheat crop at several sites across Western and Southeastern Australia, having Mediterranean environment, has been reported for different time periods of future climate by Anwar et al. (2015).

The decline in crop cycle at Mushaqar is bit lower as the mean annual minimum temperature is lower compared to Maru and this is a cooler site. The decline in crop cycle follows the trend of increase in annual mean temperature and the decline is more pronounced until 2060s decade then it slows down as in the case of increase in annual mean temperature at both the sites. On the other hand, for RCP8.5 scenario the decline starts from 5.7% and 4.2% at Maru and Mushaqar respectively, in 2010s decade and keeps decreasing to a whopping 29% and 22% decline at Maru and Mushaqar respectively, by the last decade of this century. The student's *t*-test confirmed that the decline in crop cycle was significant ($p < 0.001$) for each decade, for both CC scenarios, compared to the baseline (Table S2, supplementary data) at both Maru and Mushaqar whether CO_2 effect was considered or not.

3.3. Climate change impact on wheat yield

The impact of climate change alone *i.e.,* only the impact of change in rainfall (mainly reduction) and increased mean temperatures, reduced grain yields at both the sites for both RCP4.5 and RCP8.5 scenarios (Figs. 4a & 4b). For RCP4.5 scenario: the highest reduction of about 18% is observed in the last two decades of the century *i.e.,* 2080s and 2090s at Maru whereas about 18 and 20% at Mushaqar for those last two decades, respectively (Table 2). The reduction in yield, beginning from 2010s, is steep until the approach of 2050s decade and thereafter until 2070s it stabilizes around a decrease of 15% at Maru. More or less the percent reduction in grain yield follows the percent reduction in the days to crop maturity at Maru. However, at Mushaqar, for the same reduction in days to maturity there is a higher decrease in grain yield compared to Maru. Mitchell et al. (1993), based on their results from an experiment, attributed the direct negative effect of rising temperature on wheat yield to the temperature-dependent shortening of the phenological stages, and therefore, the time available for accumulating resources for grain formation. Similar attributions to wheat yield reductions have been made by Allen et al. (1996) and Fisher and Maurer (1976). Yang et al. (2014) report that in a Mediterranean environment the reduction of wheat yield is mainly due to shorter growth duration, where maturing time is advanced by an average of 12 days. Asseng et al. (2004) found that the APSIM was able to reproduce the shorter growth period due to warmer temperatures and thereby reduced total biomass growth and grain yields. Therefore, the results of our study affirm a degree of confidence in the simulated results using APSIM.

Until the reduction in maturity is 10%, the yield reduction is in similar proportion and once the maturity duration shortens >10%, the yield reduction is bit higher at Maru and more so at Mushaqar. The higher reduction in yield at Mushaqar can be explained by the findings of Ludwig and Asseng (2006) that the soils with higher water holding capacity, *e.g.*, soil at Maru, are most vulnerable to reduced rainfall (which is seen in our study) while soils with lower water holding capacity, *e.g.*, soil at Mushaqar, are more vulnerable to higher temperatures. It can also be observed that the reduction in rainfall was far less in Mushaqar than at Maru for both CC scenarios. For RCP4.5 scenario, at Mushaqar, for the first two decades *i.e.,* 2010s and 2020s, there is reduction in grain yield although there is slight increase in rainfall in these two decades (showing the impact of higher temperature at this site). However, in the last decade of the century there is high decrease in yield despite slight increase in rainfall establishing that the yield was reduced due to the impact of higher temperature rather than impact of rainfall.

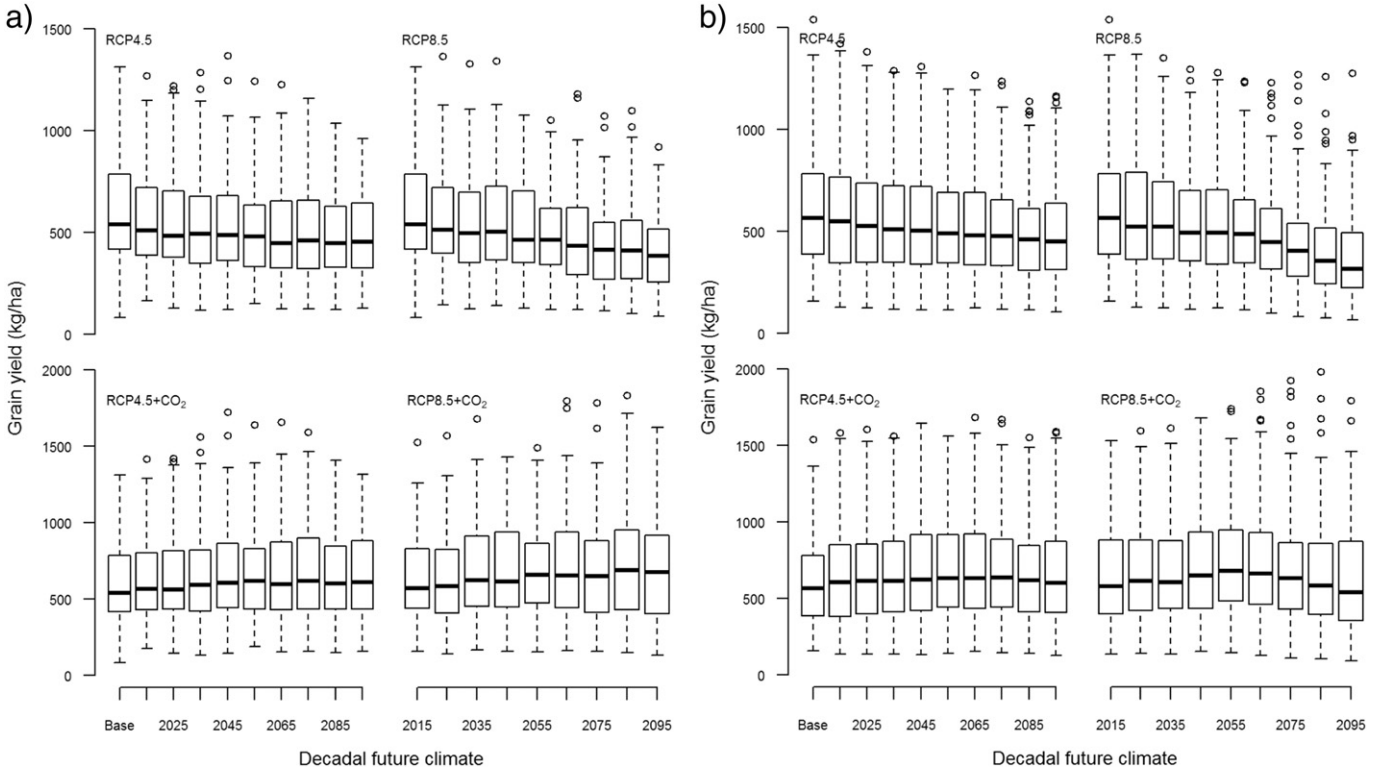

Fig. 4. Grain yield (kg ha^{-1}) for baseline and decadal future climate based on RCP4.5 and RCP8.5 climate change scenarios, with and without considering CO_2 response, at (a) Maru and (b) Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

For RCP8.5 scenario: for the first 3 decades the reduction in grain yield is <10% at both Maru and Mushaqar, however after 2030s the reduction is higher and for each coming decade keeps increasing until it reaches 33% at Maru and about 38% at Mushaqar by the last decade on this century (Table 2). Similar to our results, a 4 °C increase in ambient temperature, which corresponds to between 2060s and 2070s decade of RCP8.5 scenario (Fig. 2), reduced the wheat yield by 18% in a study by Mitchell et al. (1993). However, there is little more reduction in our case *i.e.,* about 20 and 22% for 2060s decades at Maru and Mushaqar, respectively and about 27% for 2070s decade at both the sites. The interaction of rising temperature and change in rainfall determines the final yield and in our case there was reduction in rainfall at both sites during those decades, hence more reduction in yield is observed. It is evident that in later decades the reduction in yield is more pronounced in a site having soil with lower water holding capacity, *i.e.*, Mushaqar, than with the higher water holding capacity, *i.e.*, Maru, for both CC scenarios more so for RCP8.5 scenario due to higher rise in mean temperature.

The *t*-test shows that, for RCP4.5 scenario, the reduction in grain yield was significant in the 2050s and 2060s decades ($p < 0.05$) and in the last three decades of this century *i.e.*, 2070s, 2080s and 2090s ($p < 0.01$) at Maru and in 2070s ($p < 0.05$) and in the last two decades of this century *i.e.*, 2080s and 2090s ($p < 0.01$) at Mushaqar (Table S2, supplementary data). For RCP8.5 scenario, the reduction in grain yield at both the sites was significant ($p < 0.001$) after first three decades, while for 2050s decade $p < 0.01$ at Maru and $p < 0.05$ at Mushaqar.

3.4. Climate change impact on wheat yield considering the elevated atmospheric CO_2

While the impact of climate change alone *i.e.,* only the impact of change in rainfall (mainly reduction) and increased mean temperatures, was negative on grain yield, when the impact of elevated atmospheric CO_2, which is a more realistic scenario as the elevation of CO_2 concentration is an inevitable aspect of climate change (van Ittersum et al., 2003), was considered in the simulation, the net impact was the increase in grain yield though the days to maturity more or less did not change for both CC scenarios at both the sites (Figs. 4a & 4b). These results are similar to the findings of Angulo et al. (2013) that the impact of climate change alone, without considering elevated atmospheric CO_2, reduced the wheat yield while the yield increased when CO_2 effect was added in yield simulation. Without considering the elevated CO_2 fertilization effect, crop production by 2050 and 2080 will decline across the globe. However, when CO_2 fertilization effect is included, crop production in temperate zones is reported to increase (Long et al., 2005; Parry et al., 2004; Rosenzweig and Iglesias, 1998 and Thomson et al., 2005). The results in our study show similar outcomes.

For RCP4.5 scenario: at Maru, the yield increase was about 5% in 2010s decade, thereafter it kept increasing until 2070s (Table 2). The maximum increase in grain yield, 13 and 13.5%, was observed in 2060s and 2070s decades, respectively. In last two decades, the yield increase was 11 and 11.5%, respectively. At Mushaqar however, which has soil with low water holding capacity and is a drier site compared to Maru, the increase in grain yield was higher than at Maru beginning from 2010s decade, about 7% increase, until 2070s about 15.6% increase thereafter lowering the increase to 10 and 9% in the last two decades, respectively. These results conform to the yield increase in this region reported by McGrath and Lobell (2013) per 100-ppm increase in CO_2. The maximum increase of about 16% was observed in 2060s decade. In an experiment by Mitchell et al. (1996) the elevated CO_2 concentration from 360 to 690 ppm increased the yield by 20% and by 29% in another experiment by Mitchell et al. (2001) with different soil water status where they reported that the crop with less water had greater positive effect of elevated CO_2. Further, measured and simulated effect of CO_2 on wheat was reported to be 10 and 12% for the wet, and 20 and 34% for dry treatments when CO_2 was increased from 360 to 550 ppm indicating that the CO_2 effect on grain mass is higher under water limitation for both the measured and the simulated results (Grossman-Clarke et al., 2001). Luo et al. (2009) found that the simulated negative impact on wheat grain yield was less pronounced in soil with lower water holding capacity at South Australian sites, under Mediterranean climate with an elevated CO_2 of 682 ppm using APSIM. Hence, the higher positive effect in yield at Mushaqar due to elevated CO_2 effect, along with the other climate change variables, was seen in our study. Other similar studies (Anwar et al., 2015; Asseng et al., 2004; van Ittersum et al., 2003; Yang et al., 2014) have reported results corroborating with our study when they used APSIM to simulate wheat yield. This shows that while the absolute increase in yield may be low in the drier soils and soils with low water holding capacity, the negative effect of climate change, if any, especially with elevated CO_2 will be lower. In fact, at the sites in this study, based on above results, there will be higher positive impacts of CC in this environment more so at the drier sites or sites with sandy soils until 2070s for a moderate CC scenario like RCP4.5. However, in the absolute terms this may not have much improvement in the yield because the yield is generally lower in the soils with low water holing capacity.

In the case of RCP8.5 scenario, although the increase in mean temperatures and overall decrease in rainfall was higher than RCP4.5 scenario at both the sites yet due to the higher atmospheric CO_2 concentration (Table 1), and positive effect of CO_2 at higher temperature (van Ittersum et al., 2003), there was a positive impact on grain yield and an increase in wheat yield was observed. In this case however, generally there was more increase in grain yield at Maru than at Mushaqar unlike RCP4.5 scenario because it was site of high water holding capacity. Due to higher increase in temperature for RCP8.5 scenario, as reported by Ludwig and Asseng (2006) that soils with lower water holding capacity, *e.g.*, soil at Mushaqar, are more vulnerable to higher temperatures, there was more drastic effect of higher temperature on yield at Mushaqar, though counter balanced by the increased CO_2 to some extent. Nevertheless, there was overall positive impact due to elevated atmospheric CO_2 concentration similar to the results of wheat simulations by Angulo et al. (2013) when the highest increase was for the scenario when temperature and CO_2 increase was the highest similar to RCP8.5 scenario in this study.

Overall, when CO_2 effect was considered, no negative impact of shorter life cycle on grain yield was found for both CC scenarios at both the sites. Generally, the case is that the shorter duration varieties tend to be lower yielding than a longer duration variety, because the crop may not get enough time for photosynthesis and hence biomass accumulation (Asseng et al., 2015; Sommer et al., 2013). This simulation study affirms that in this environment, irrespective of mean temperature increase of 3 °C for RCP4.5 scenario and 5.5 °C for RCP8.5 scenario (Table 1), and consequently reduction of up to 16 and 29 days (Figs. 3a & 3b) in crop cycle for RCP4.5 scenario and RCP8.5 scenario respectively, the unfavorable effect of increased temperature (and decreased rainfall) was negated by the elevated atmospheric CO_2 effects even on top of that positive effect on yield was observed. Rosenzweig (1989) found that the combined effects of climate change and increased CO_2 produced a net increase in wheat yields in the great plains of the U.S. when they simulated wheat yield using a crop model. Although some researchers (Luo et al., 2005; Luo et al., 2009; Parry et al., 2004) have reported negative yields even considering CO_2 impact because the overall impact of climate change varies in different regions. Crop yield generally responds positively to increased atmospheric CO_2 concentration though the response depends on the crop species and environmental conditions and the regional yield response to increased CO_2 varies (McGrath and Lobell, 2013) and under some conditions, where some other growth factor is severely limiting, such as low temperature, the CO_2 fertilization effect may not be manifested (Long, 1991) and hence no gains in yield can be expected in such environment. The overall effect on grain yield is determined by the amount and mechanism the temperature, humidity and light modify the response of plants to elevated CO_2 (Ainsworth et al., 2002). Kimball (1983), from an exhaustive survey of

over 1000 chamber studies, showed that elevation of CO_2 to 660 ppm caused an average 33% increase in yields for C_3 crops, with a range of 24–43%. Long et al. (2005) considered the estimated elevation of CO_2 to be about 560 ppm by 2050, which is similar to RCP8.5 scenario for 2050–2060 decade in this study, which approximates the level used in large-scale FACE experiments with food crops. The 33% increase observed at 660 ppm translates to 23% at 560 ppm assuming a linear response. In our study, the increase in yield for RCP8.5 scenario and 2050–2060 decade was about 18% at both Maru and Mushaqar sites. Similar magnitude of increase in wheat yield, 22% across western Europe (Bender et al., 1999; Long et al., 2005), 19% in Europe (Ewert et al., 2005), 23% in US (Thomson et al., 2005) and 33% in US and Canada (Rosenzweig and Iglesias, 1998) have been reported for different regions in temperate zones with elevation of CO_2 to 550–575 ppm. O'Leary et al. (2015) found 26% increase in wheat grain yield during Free-Air CO_2 Enrichment (FACE) experiment and 28% increase in simulation using APSIM with elevated CO_2 from 365 to 550 ppm in semi-arid Mediterranean environment.

The combination of temperatures, rainfall and CO_2 determines the overall impact on yield. Temperature increases are likely to support positive effects of enhanced CO_2 until temperature thresholds are reached. Beyond these thresholds, crop yields will decrease despite enhanced CO_2 (Singh et al., 2014b). This is seen in later decades of both CC scenarios and at both the sites when increase in yield declines even if CO_2 levels keep increasing. The highest increase at Maru was about 20% in 2080s decade, whereas it was about 18% at Mushaqar in 2050s decade (Table 2). For year 2050, which falls between 2045 and 2055 *i.e.,* 2040s and 2050s decades, the increase in yield was about 15% at Maru and 14.5% at Mushaqar respectively, taken linearly as Cammarano et al. (2012) found that there was linear increase in simulated wheat yield when CO_2 was increased from 380 ppm to 500 ppm and then to 600. These results are similar to Angulo et al. (2013) who report an average 14% increase in simulated wheat yield with increased CO_2 for 2050. These results also corroborate with the findings of Ainsworth and Long (2005) and Manderscheid and Weigel (2007) during their FACE experiments for C_3 crops. It is possible that sometimes the crop models may produce more pronounced impact of climate change on yield because they primarily consider the effect of modified climate on the crop growth and development and do not consider the change in weed and diseases infestation due to climate change (Angulo et al., 2013; Savary et al., 2006). It does however highlight that irrespective of some losses, if any, there are certainly going to be overall gains in wheat production and farmers are, in any case, not going to suffer yield losses that they already expect when they think about the climate change. Moreover, the effective agro-techniques (physical, biological and chemical methods) and genetic improvements of the cultivars (*e.g.,* weeds, pests and disease resistant cultivars) are also expected to provide effective fight to weeds, pests and diseases. Hence when these agro- technologies and adaptation measures are employed, which the Government is already encouraging and evident from the yield trends mentioned earlier, will overall have less reduction in losses due to weeds, pests and diseases and more favorable impact of future climate will be observed in the region.

Based on the *t*-test, the increase in grain yield was not significant at Maru for RCP4.5 scenario, though weakly significant in 2040s, 2060s and 2070s decades ($p < 0.1$) (Table S2, supplementary data). Nevertheless, there is potential to exploit the increase in grain yield due to the positive CO_2 effect on yield. The increase in yield was significant at Mushaqar in 2050s, 2060s and 2070s decade ($p < 0.05$) and weakly significant in 2040s ($p < 0.1$) for RCP4.5 scenario. For RCP8.5 scenario, the increase in yield at Maru was significant in all the decades ($p < 0.01$ for 2040s and 2080s decades and $p < 0.05$ for 2030s, 2050s–2070s and 2090s) except the first two decades. While at Mushaqar, the increase in yield was significant ($p < 0.05$) in 2050s and 2060s decade and weakly significant ($p < 0.1$) in 2030s and 2070s decades.

The above results show that in coming future the farmers can expect to gain from wheat production in this dry Mediterranean climate of Jordan or indeed countries having similar climates *e, g.,* Egypt, Israel, Lebanon, Morocco, Syria, Tunisia *etc.*. Because the crop matures early due to climate change, there is potential to deploy long duration cultivars and obtain further yield gains (similar arguments have been made by Cooper et al., 2009).

3.5. Transpiration use efficiency

Firstly, the impact of mean temperature increases and change in rainfall (mainly reduction) due to climate change was observed in the transpiration use efficiency (TUE) of the wheat crop *i.e.,* the amount of grain produced (kg ha^{-1}) per mm of water transpired from the wheat crop. This has direct bearing on the grain yield of water-limited wheat production. At Maru: the TUE for baseline climate was 24.3 kg ha^{-1} mm^{-1} (Fig. 5) and was reduced by 6.3% for RCP4.5 scenario for 2010s decade. Thereafter, based on the incremental increase in temperature for each decade for the same CC scenario, the decrease was fairly low *i.e.,* <1% except for 2050s decade when the decrement was 1.5% and the last decade of this century when there was an incremental increase of 1.7% compared to immediately previous decade because in this decade there was slight increase in rainfall for RCP4.5 scenario (Table 1). There was about 6% decrease in TUE by 2080s decade, when highest reduction was observed, compared to 2010s decade for RCP4.5 scenario and about 21% by 2090s decade for RCP8.5 scenario. However, at Mushaqar: where the baseline TUE was 19.5 kg ha^{-1} mm^{-1} (Fig. 5), except for 2040s and 2070s decades when the TUE increased by an increment of about 2%, the increment or decrement was within a percent for all other decades. The maximum decrease of only 0.5%, compared to 2010s decade, was observed by the 2060s decade for RCP4.5 scenario and about 5% by 2090s decade for RCP8.5 scenario at Mushaqar. The change in TUE is governed by the increase in maximum and minimum temperature and the available soil water (Dixit and Chen, 2010b) (which is governed by the rainfall in this dry environment) for a particular site.

For RCP8.5 scenario, except for first two decades when the TUE is higher than that of RCP4.5 scenario, the TUE keeps reducing to a value of 19.1 kg ha^{-1} mm^{-1} with a decrement of 1.5 to 3.5% until the last decade of this century at Maru. At Mushaqar, however the change in TUE from RCP4.5 to RCP8.5 scenario was not large except for last 3 decades when a step decrease of about 2.2% is observed in 2080s decade compared to immediate previous decade.

Secondly, when the effect of CO_2 was considered in the grain yield simulation, the TUE increased for both CC scenarios more so for RCP8.5 scenario at both Maru and Mushaqar and more dramatically at Mushaqar compared to Maru. At Maru: for RCP4.5 scenario, during the 2010s decade there was about 5% increase in TUE when CO_2 effect was also considered compared to when only the impact of reduced rainfall and increased mean temperatures, was considered. The TUE considering CO_2 effect kept increasing up to 19% by the last decade of this century (Fig. 5) for RCP4.5 scenario. For RCP8.5 scenario, there was more dramatic increase in TUE when CO_2 effect is considered beginning at 5.5% in 2010s decade to a whopping 55% by the last decade of this century. Overall, when CO_2 effect was considered, there was about 8.5% increase in TUE from 2010s decade to 2090s decade for RCP4.5 scenario and about 22% increase for RCP8.5 scenario at Maru. At Mushaqar: the results of TUE increase, when CO_2 effect was considered, compared to when only the impact of reduced rainfall and increased mean temperatures was considered, were of similar magnitude to Maru for each decade and for each CC scenario. However, the increase between 2010s decade and 2090s decade was higher at Mushaqar, compared to Maru and there was about 14.5% increase in TUE from 2010s decade to 2090s decade for RCP4.5 scenario and about 39% increase for RCP8.5 scenario. Within each decade, on an average, there was an increment of 0.7% for RCP4.5 scenario and 2.2% for RCP8.5 scenario at Maru and an increment of 2.1% for RCP4.5 scenario and 4.5% for RCP8.5 scenario at Mushaqar. Hence at Mushaqar, which is a site with soil having

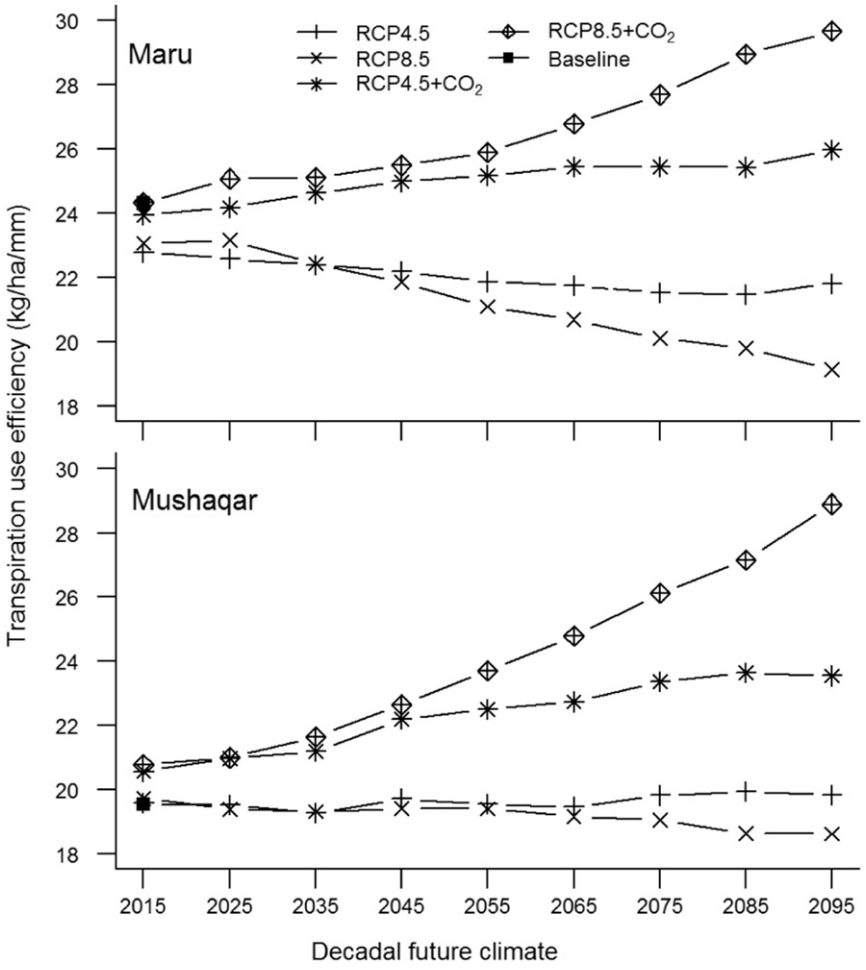

Fig. 5. Transpiration use efficiency (kg ha^{-1} mm^{-1}) of wheat yield production for baseline and decadal future climate based on RCP4.5 and RCP8.5 climate change scenarios, with and without considering CO_2 response, at Maru and Mushaqar, Jordan. Year 2015 represents 2010–2020 decade, year 2025 represents 2020–2030 decade and so on.

lower water holding capacity and relatively cooler mean temperatures and lower rainfall compared to Maru, the increase in TUE was higher in each decade for both RCP4.5 and RCP8.5 scenario compared to Maru. The overall transpiration use efficiency, and hence water use efficiency of the crop production, is increased due to reduced transpiration and shortening of the crop cycle as the elevated CO_2 decreases water use at both the leaf and canopy scale (Leakey et al., 2009). Mitchell et al. (2001) reported 21% increase in TUE of a wheat crop when CO_2 was elevated from 360 to 690 ppm. In a review study, Long et al. (2004) reported that with elevated CO_2 concentration, the transpiration decreases and a gain in yield can be foreseen due to improved plant water status. It has been well documented that one of the effects of increased CO_2 is a reduction in transpiration (Kimball et al., 1995). An increase in TUE of a wheat crop from 18.3 kg ha^{-1} mm^{-1} at baseline climate (1961–1990) to 25.8 kg ha^{1} mm^{-1}, for long-term future (2071–2100) is reported by Sommer et al. (2013) with higher TUE for A2, a more drastic scenario than A1B, a balanced scenario of SRES. In similar fashion, the increase in TUE is higher in more drastic RCP8.5 scenario than less drastic RCP4.5 scenario in our study. Also the magnitude of increase in TUE in above study is similar to our findings in case of RCP8.5 scenario *e.g.*, from 19.5 kg ha^{-1} mm^{-1} at baseline climate to 27.1 kg ha^{1} mm^{-1} for 2085 (corresponding to period 2071–2100) (Fig. 5). Seasonal water use decrease from 320 to 301 mm by CO_2 increase from 365 to 550 ppm, increasing water use efficiency for yield by 31% in a FACE experiment, and that APSIM simulation results mimicked this experimental response, has been reported by O'Leary et al. (2015). Increased CO_2 concentration in the atmosphere causes partial stomata closure, therefore, reduces the loss of water from the crop as transpiration (Singh et al., 2014b), reducing transpiration and thereby increasing the transpiration and water use efficiency which can be exploited by crop growers to achieve more yield for less amount of water.

The change in TUE was in almost perfect positive correlation with the atmospheric CO_2 concentration (Fig. S1, supplementary data) at both Maru and Mushaqar sites (considering CO_2 elevation for both RCP4.5 and RCP8.5 scenarios). The higher the atmospheric CO_2 concentration, the higher is the improvement in TUE. For every 100-ppm increase in atmospheric CO_2 concentration, there was an increase of TUE by 2 kg ha^{-1} mm^{-1}. Hence, the elevated level of CO_2 is directly responsible for increasing transpiration use efficiency of wheat crop in this dry Mediterranean environment. These results are significant in projecting the water requirement of the crop and potential conservation of water resources to exploit the positive effect of atmospheric CO_2 concentration on wheat yield in this region as the increased TUE translates into overall improved water use efficiency. Even for most drastic scenario like RCP8.5, the effect of CO_2 concentration is going to be in favor of wheat farmers by means of increase in yield and lower water requirement of the crop.

4. Conclusions and way forward

Considering the similar results of other studies on the impact of climate change, as mentioned above, APSIM appears to perform well in crop cycle, yield and transpiration use efficiency simulation of wheat at decadal level based on two prominent climate change scenarios *viz.*, RCP 4.5 and RCP8.5. This study indicates that without considering the

atmospheric CO_2 concentration, the future climate will negatively impact wheat yield in Jordan and in dry Mediterranean environments with similar climate. However, the elevation in atmospheric CO_2 concentration due to climate change is expected to negate the impact of increased temperatures and reduced rainfall for both a moderate *i.e.*, RCP4.5 and a drastic *i.e.*, RCP8.5 scenarios of climate change. While the drier sites and sites with soil having low water holding capacity will have higher positive impact of elevated CO_2 with moderate increase in mean temperature, a higher positive impact of elevated CO_2 can be foreseen at less drier sites and sites with soil having high water holding capacity at higher increase in mean temperature. On an average, a grain yield increase of 5 to 11% in near future *i.e.*, 2010s–2030s decades, 12 to 16% in mid future *i.e.*, 2040s–2060s decades and 9 to 16% in end of century period can be expected for moderate climate change scenario and 6 to 15% in near future, 13 to 19% in mid future and 7 to 20% increase in end of century period for a drastic climate change scenario based on different soils. It appears that as the end of the century approaches, yield increases due to CO_2 effect stabilized and are even attenuated due to higher increase in temperatures. The transpiration use efficiency will be increased in the future for all CC scenarios and thereby, in this environment yield gains are expected in future and farmers can benefit from growing wheat even with less available water. The elevated CO_2 will not affect reduction in crop cycle due to increased mean temperatures and overall the crop maturity will shorten by a fortnight and a month for moderate and drastic scenario of climate change respectively, by the end of the century. The reduction in crop cycle *i.e.*, crop maturing early gives opportunity to deploy longer duration wheat cultivars and achieve even higher yield. However, the study has to be conducted if the farmers are indeed going to benefit from the longer duration crops because sometimes due to change in rainfall during grain-filling period, there may be a case of terminal drought or even impact of extreme temperatures (Dixit and Chen, 2010a, 2011) on grain yield.

Several adaptation measures can be used to exploit the yield benefits due to climate change to further enhance the yield *e.g.,* shifting planting window and employing existing and improved varieties (Rosenzweig and Parry, 1994) which may perform well in the affected region. Early planting in Mediterranean climate of South Australia (Luo et al., 2009) and subtropical climate of Queensland (Cammarano et al., 2012) has been reported as an adaptation strategy to climate change. Conservation agriculture *e.g.*, zero-tillage, residue retention (Ortiz et al., 2008), improved wheat varieties with longer crop cycle and heat and drought tolerant varieties (Boote et al., 2011; Wang et al., 1992; Yang et al., 2014) can be adaptation measures to further increase yield. Higher nitrogen fertilization give higher yield due to elevated CO_2 (Rosenzweig et al., 2014) and hence by applying sufficient nitrogen fertilizer, significant increase in yield and financial return, as a benefit of climate change, can be achieved as demonstrated by van Ittersum et al. (2003) in a simulation study. Hence, a systematic study should be conducted to ascertain the extent to which certain adaptation measures and their combination will be helpful and thereby determine the economic benefits of climate change in this environment which can help farmers formulate their input resources based on future climate during a particular decadal period.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.07.270.

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